$Ta_{34}Nb_{33}Hf_8Zr_{14}Ti_{11}$ – The First Observation of Superconductivity in High-Entropy Alloys

Primož Koželj[1,*], S. Vrtnik[1], A. Jelen[1], S. Jazbec[1], Z. Jagličić[2], S. Maiti[3], M. Feuerbacher[4], W. Steurer[3] and J. Dolinšek[1]

[1] Jožef Stefan Institute and University of Ljubljana FMF, Ljubljana, Slovenia
[2] Institute of Mathematics, Physics and Mechanics and University of Ljubljana FGG, Ljubljana, Slovenia
[3] ETH Zürich, Department of Materials, Laboratory of Crystallography, Zürich, Switzerland
[4] Institut für Mikrostrukturforschung, Forschungszentrum Jülich, Jülich, Germany

[*]primoz.kozelj@ijs.si

High-entropy alloys (HEAs) [1,2] are the most recent in a series of modern alloy design strategies (QCs, CMAs, bulk amorphous glasses) that abandon the traditional one-principal-element design paradigm. The novelty of this particular approach lies in the fact that HEAs – multicomponent mixtures of elements in similar concentrations – are made stable by the high entropy of mixing of their disordered solid solution phases. Studies into the (micro)structural and mechanical properties of HEAs have found technologically favourable properties [1] such as high hardness, excellent resistance to anneal softening, high-temperature strength, excellent ductility, etc. The observed physical properties have been less remarkable [3] – the electrical and thermal conductivities are 1 to 2 orders of magnitude smaller than in conventional metals (due to the highly disordered lattice scattering of electrons and phonons). Furthermore, HEAs containing magnetic elements exhibit rather standard paramagnetism or ferromagnetism.

My colleagues and I have been fortunate to have our efforts rewarded by the discovery of $Ta_{34}Nb_{33}Hf_8Zr_{14}Ti_{11}$ – the first HEA with a phase transition to a superconducting (SC) state [4]. The observation of superconductivity in a new group of materials is always interesting from the view-point of physics and I will therefore briefly report and discuss the observed properties. Our sample had the composition $Ta_{34}Nb_{33}Hf_8Zr_{14}Ti_{11}$ (determined by EDS spectroscopy) and possessed an average body-centered cubic structure of lattice parameter $a = 3.36$ Å. The lattice properties (lattice parameter, Debye temperature) obey Vegard's rule of mixtures, thus indicating completely random mixing. Measurements of the magnetization, specific heat and electrical resistivity were conducted and have revealed that $Ta_{34}Nb_{33}Hf_8Zr_{14}Ti_{11}$ is a type II superconductor and that its behavior is close to a BCS-type phonon-mediated superconductor in the weak electron-phonon coupling limit. Additionally, the previously-mentioned huge amount of disorder (randomness) further classifies $Ta_{34}Nb_{33}Hf_8Zr_{14}Ti_{11}$ as a "dirty" superconductor. From the measurements of the physical properties we have determined the transition temperature $T_c \approx 7.3$ K, the upper critical field $\mu_0 H_{c2} \approx 8.2$ T, the lower critical field $\mu_0 H_{c1} \approx 32$ mT, and the energy gap in the electronic density of states (DOS) at the Fermi level of $2\Delta \approx 2.2$ meV. The formation of the SC state lowers the energy, but not enough to compensate the diminished entropic stabilization at low temperature and thus stabilize the disordered state – we therefore conclude that our HEA is metastable.

[1] J.W. Yeh, *et al*, Adv. Eng. Matter. **6**, 299 (2004).

[2] J.W. Yeh, Ann. Chim. Sci. Mat. **31**, 633 (2006).

[3] M.H. Tsai, Entropy **15**, 5338 (2013), and references therein.

[4] P. Koželj, S. Vrtnik, A. Jelen, S. Jazbec, Z. Jagličić, S. Maiti, M. Feuerbacher, W. Steurer, and J. Dolinšek, Phys. Rev. Lett. **113**, 107001 (2014).